Carderock Division
Naval Surface Warfare Center
West Bethesda, MD 20817-5700

NSWCCD-65-TR–2001/21 October 2001

Survivability, Structures And Materials Directorate

Technical Report

Long-Term Health Monitoring of the Composite Road Bridge on Delaware Route 896

by

Colin P. Ratcliffe

Roger M. Crane

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NSWCCD-65-TR–2001/21 Long-Term Health Monitoring of the Composite Road Bridge on Delaware Route 896

DEPARTMENT OF THE NAVY

NAVAL SURFACE WARFARE CENTER, CARDEROCK DIVISION
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From: Commander, Naval Surface Warfare Center, Carderock Division
To: Chief of Naval Research (ONR 332)

Subj: COLLABORATIVE STRUCTURAL EVALUATION OF A HIGHWAY COMPOSITE DECK BRIDGE

Ref: (a) Program Element 0602234N, Seaborne Structures Materials Program

Encl: (1) NSWCCD-65-TR–2001/21, *Long-Term Health Monitoring of the Composite Road Bridge on Delaware Route 896*

1. Reference (a) requested the Naval Surface Warfare Center, Carderock Division (NSWCCD) to perform an ongoing investigation into using broadband vibration data to monitor the structural integrity and health of an all-composite road bridge. Enclosure (1) contains the vibration data which were obtained for the year 2001 (the third consecutive year) as part of an effort to continue to develop a vibration-based, non-destructive evaluation method suitable for long-term inspection of composite structures. The report covers the most recent data collection on an all-composite bridge and compares the modal results with those obtained from previous years.

2. Comments or questions may be referred to Dr. Roger M. Crane, Code 6553; telephone (301) 227-5126; e-mail, CraneRM@nswccd.navy.mil.

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Subj: COLLABORATIVE STRUCTURAL EVALUATION OF A HIGHWAY COMPOSITE DECK BRIDGE

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Survivability, Structures, and Materials Directorate

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14. ABSTRACT
This report presents the results of an ongoing investigation into using broadband vibration data to monitor the structural inegrity and health of a composite road bridge. The bridge deck configuration is of sandwich construction, as are the Joint Modular Lighter System (JMLS) and the LPD-17 mast, which are currently under development by the U.S. Navy. Demonstrating the ability to determine the structural health and any degradation in properties of the Route 896 bridge in its service environment would illustrate the utility of the broadband vibration technique for Navy structures. The primary development being reported here is the ability to determine changes in the structural integrity of the bridge from the first inspection performed in 1999 compared with the state of the structure in 2001. This development will provide guidance for the locations that are showing changes in their structural integrity as the structure ages. This comparison is being performed using the Structural Integrity and Damage Evaluation Routine (SIDER) which is being developed to assist in the health monitoring of large structures.

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Administrative Information

The work described in this report was performed by the Structures and Composites Department of the Survivability, Structures, and Materials Directorate, at the Naval Surface Warfare Center, Carderock Division (NSWCCD), in conjunction with the United States Naval Academy. The work was funded by the Office of Naval Research, Code 332, under the Seaborne Structures Materials Program (PE 0602234N) under the guidance of Mr. James J. Kelly.

Acknowledgements

The authors would like to acknowledge the support by the Delaware Department of Transportation (DelDOT) for the personnel to close the bridge so that the inspection could be performed and for providing the rowboat to allow for the underside inspection. In addition, the authors would like to thank the University of Delaware for their support in carrying out the bridge inspection.

Summary

Composites are gaining increased use as a structural material for Navy applications. Two applications where composite materials are currently being used are the masts for LPD-17 class ships and the Joint Modular Leighter System (JMLS). With structures of this size, methodologies for ensuring the structural integrity become very important. Although inspection techniques are available which can be readily implemented in a laboratory setting, few exist which can be used in the type of service environment to which the aforementioned applications are subjected.

This report presents the results of an ongoing investigation into using broadband vibration data to monitor the structural integrity and health of an all-composite road bridge. More specifically, this report presents results of the third inspection of the bridge I-131 on Business Route 896 located in Glasgow, Delaware. The bridge consists of two E-Glass/vinyl ester sections (each 13 ft x 32 ft) joined by a longitudinal joint in the traffic direction. Each section is a sandwich construction consisting of a 28-inch deep core and a 0.5-0.6 inch thick facesheets. The bridge deck configuration is of sandwich construction, as are the LPD-17 mast and the JMLS, which are currently under development by the U.S Navy. This third vibration inspection was performed to establish the changes occurring during the service life of this civil structure. Demonstrating the ability to determine the structural health and any degradation in properties of the Route 896 bridge in its service environment would illustrate the utility of the broadband vibration measurement technique for Navy structures.

Vibration data were obtained from a mesh of 1050 test points located on a regular array on the upper and lower facesheets of the bridge. The mesh that was used for this third inspection is identical to that used in the prior two inspections. From the modal information and the visualization of the data, several aspects of the structural behavior of the bridge will be reported and compared to the prior years' inspections. The primary development being reported herein is the ability to determine changes in the structural integrity of the bridge from the first inspection performed in 1999 compared with the state of the structure in 2001. This development will provide guidance for the locations that are showing changes in their structural integrity as the structure ages. This comparison is being performed using the Structural Integrity and Damage Evaluation Routine (SIDER), which is being developed to assist in the health monitoring of large structures (References 1 and 2). Demonstrating the ability to determine the structural health and any degradation in properties of the Route 896 bridge in its service environment potentially illustrates the utility of the broadband vibration technique for Navy structures

The report presents a comparison of the modal results with those obtained from previous years. This SIDER analysis is also conducted on the prior years testing information, and the results are presented herein. Since the SIDER analysis has been substantially developed and modified during three-year effort on the bridge, this report will detail those changes. The SIDER results locate local variations in a structure, and how that variation is changing with time. This SIDER analysis is a further development to establish and develop a vibration-based non-

destructive evaluation method suitable for long-term inspection of large-scale composite structures.

Background

A research and educational collaboration initiated in the early 1990s by the University of Delaware Center for Composite Materials (CCM), the University of Delaware Department of Civil and Environmental Engineering (CEE), and the Delaware Transportation Institute (DTI) culminated in the installation of an all-composite bridge deck on Business Route 896 in Glasgow, Delaware. Other partners in the project were the Delaware Department of Transportation (DelDOT), the Federal Highway Administration (FHWA), and local industry and contractors including Hardcore Composites, Anholt Technologies, and James Julian, Inc.

The bridge is identified in the Delaware highway system as Bridge 1-351. It is situated at approximately 39°36.63'N 75°44.77'W and carries Route 896 over a small stream known locally as Muddy Run. During the vibration trial reported here, the Muddy Run water under the bridge was several inches deep at the sides, increasing to about 3 feet in the middle. The water level was comparable to the levels during the trials conducted in 1999 and 2000.

Many details of the vibration analysis of this bridge are included in References 3 and 4 (May 99 and June 2000 reports). The reader is directed to those references for more details on the experimental aspects of the vibration test and structural features of the bridge.

The new bridge was installed and opened to traffic on November 20, 1998. This bridge carries a single-lane one-way road. Figure 1 is a panorama of the bridge, compiled from several still images. In this picture, north is left and south is right.

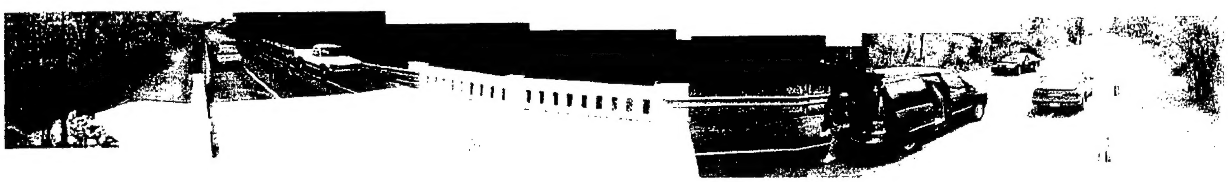

Figure 1. Panoramic View of Composite Bridge Deck

The focus of the vibration trial reported here was to obtain a large quantity of frequency-based vibration data from the bridge deck. These data are for analysis as well as being archived for later work. This report includes the results of the modal analysis, and a comparison with the previous modal results from 1999 and 2000. The results of applying the SIDER broadband damage detection method are also presented and discussed.

Key Personnel

The following were the key on-site personnel involved in this May 2001 vibration trial.

Professor Colin P. Ratcliffe, United States Naval Academy (USNA);

Dr. Roger M. Crane, Naval Surface Warfare Center, Carderock Division (NSWCCD);

Professor John W. Gillespie, Jr., Dr. Dirk Heider, and Dr. Ken Yoon, The Center for Composite Manufacturing (CCM);

A team of employees of the Delaware Department of Transportation (DelDOT) who closed the bridge, provided on site support such as supplying a boat, and provided safety numbers to ensure traffic did not pass the barricades.

Schedule

The following summarizes the actual trial phase of the project.

Tuesday May 29th

CCM personnel on site to check mesh markings remaining from the June 2000 trial. Mesh was measured and repainted where it was missing (worn off).

Wednesday 30th

0815 Arrive on site. Start laying out cables.

0830 Bridge closed to traffic. Reinstall accelerometers at same locations as for 2000, and run all cables. Waterproof all connections and transducers. Prepare analyzer.

1015 Commence data capture for impacting the underside of the bridge.

1253 Underside data capture complete. 512 data files were recorded. This represents 3.24 measurements per minute, which compares to 2.96 measurements per minute in June 2000.

1315 Commence data capture for topside.

1532 Topside data capture complete. 573 data files were recorded for this phase. This represents 4.18 measurements per minute, which compares to 3.72 measurements per minute for June 2000.

1545 Bridge reopened to traffic. Depart for Maryland, start data translation en-route.

1645 While still on the road, SIDER results generated, and provisional modal results from first three modes available.

Bridge General Description

A more detailed description, including a survey of the bridge dimensions, is included in Reference 3. For this project, the bridge can be considered to have three main components; two guardrails, and one deck. Dynamically, these components are decoupled by rubber seals installed between each guardrail and the deck. The main components of the bridge are shown in Figure 2 through Figure 4, which are copied from References 3 and 4. The deck is the main component of interest for this project. It is approximately 26 feet wide and 32 feet long, and sits on abutments at the north and south banks. The deck was manufactured in two parts, each approximately 32 feet long and 13 feet wide. The two parts are joined by a longitudinal north-south joint, which can be seen in Figure 4, which shows the under side of the bridge.

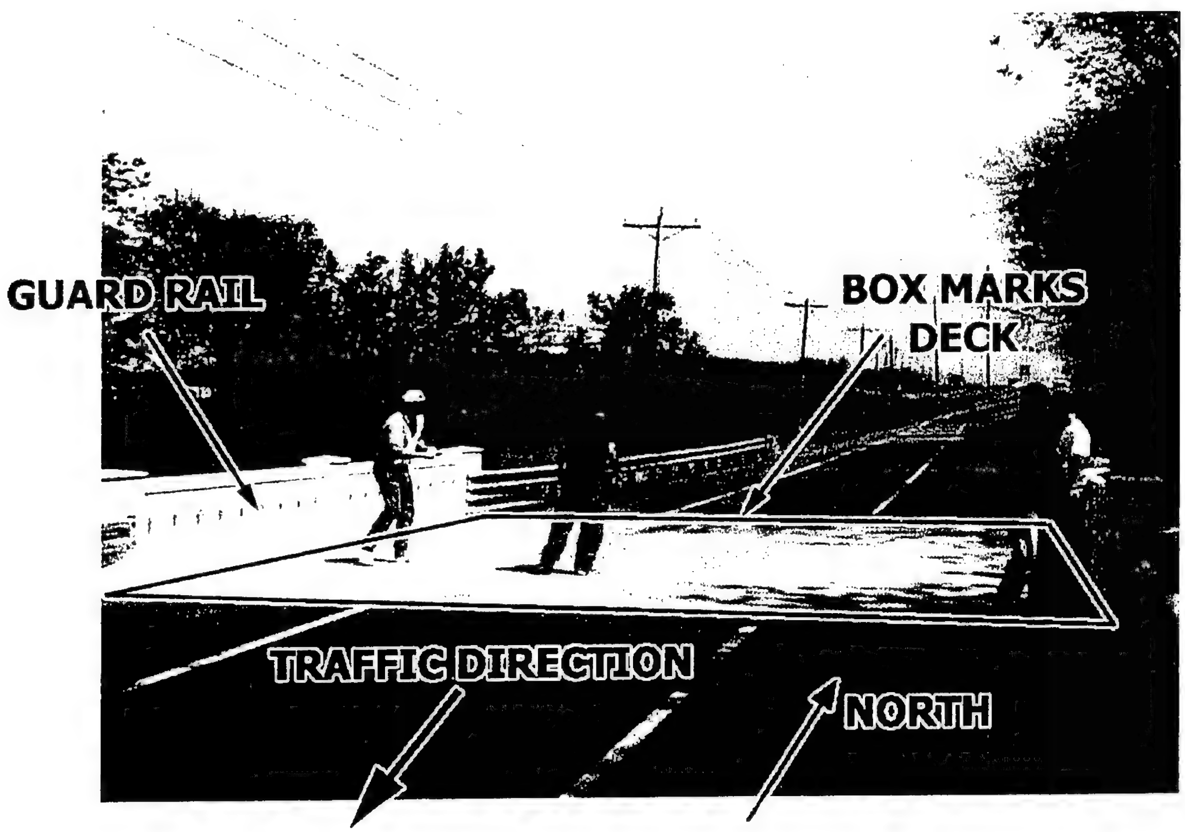

Figure 2. View of Bridge Deck Components (Top)

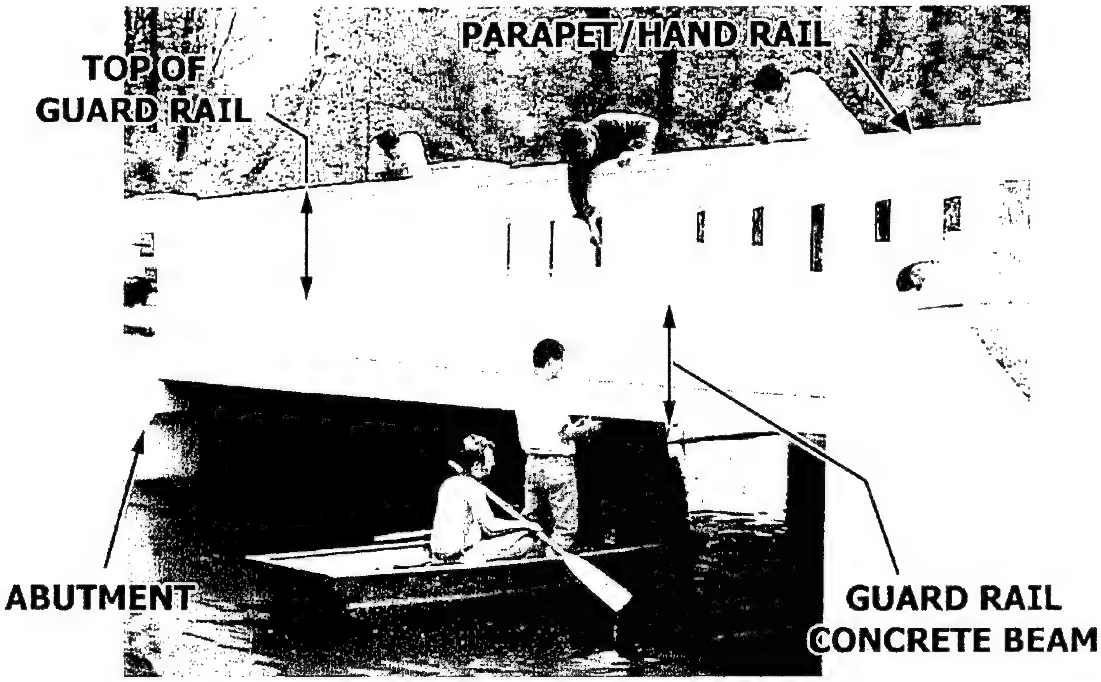

Figure 3. View of Bridge Deck Components (Side)

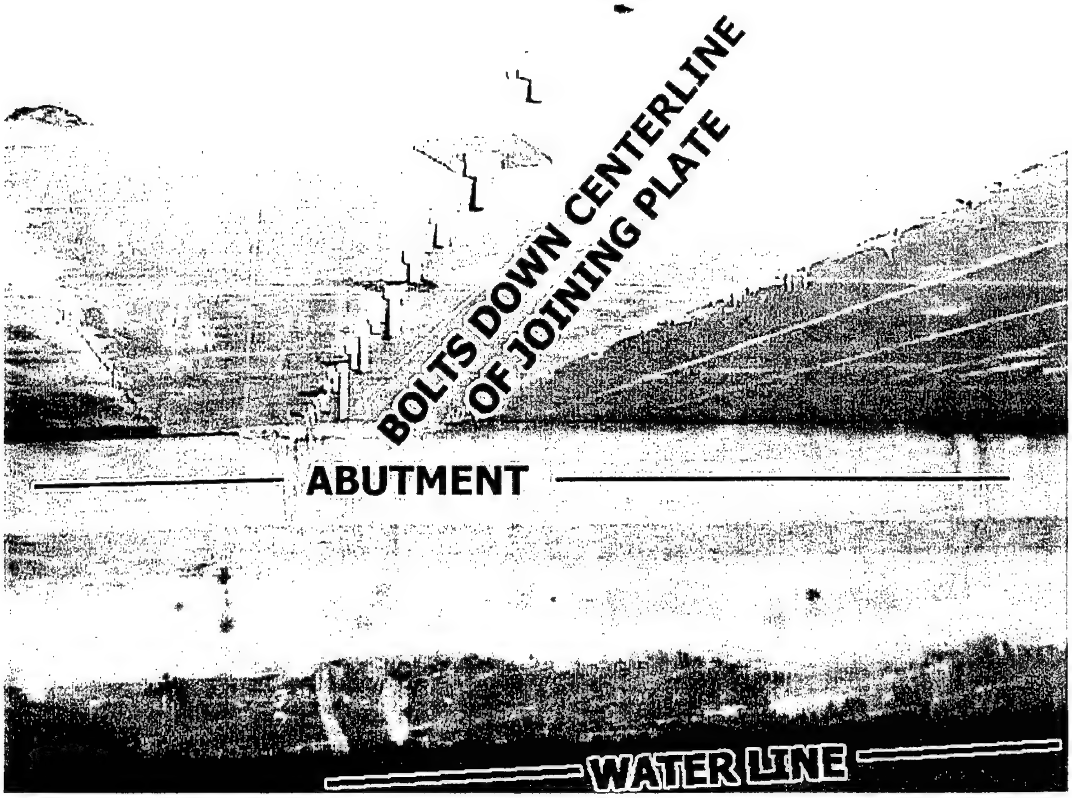

Figure 4. View of Underside of Composite Bridge Deck,
Looking North with Centerline Joint

Survey

As part of the May 1999 trial, the bridge was surveyed. The global origin for all measurements was taken as the extreme southeast corner of the concrete guardrail at deck level – this being a point on the bridge unlikely to be damaged or moved by traffic or other accidents. The X-axis was parallel to the line of the bridge (pointing approximately north); the Y-axis was across the bridge (pointing approximately west); and the Z-axis pointed upwards. The axis origin was at the height of the top bridge deck. The small curvature of the deck surface was ignored; all test points on this surface being assigned zero Z-coordinate values. As a result of this origin location and ignoring the surface slope, all test points on the bottom surface had the same negative Z-coordinate value (-30 inches).

The Test Grid – General

The mesh of test grid points consists of two sub meshes; one on the top surface and one on the bottom surface. Both meshes were uniform, with an 18-inch spacing in the X- (north-south) direction, and a twelve-inch spacing in the Y- (east-west) direction. This is the identical grid arrangement as used in May 1999 and June 2000. The mesh was re-established in exactly the same way as in References 3 and 4, and thus the procedure and details are not repeated here.

The Test Grid – Accelerometers

As for the May 1999 and June 2000 tests, four accelerometers were used to record the motion of the deck. The installation is identical to the information presented in References 3 and 4, and is not repeated here.

Equipment

The reader is directed to References 3 and 4 for details of the accelerometers, force gage and analyzer. The identical equipment and settings were used this year.

Data Capture

Based on the successful experiences of the May 1999 and June 2001 trials, each coordinate was impacted two times, and the frequency response functions were frequency averaged. Care was taken to repeat the data capture for a particular coordinate if there was the slightest doubt as to data quality. Data were again captured in the frequency range 0-1 kHz, with a frequency resolution of 0.625 Hz and a real-time measurement of 1.6 seconds per impact. The exponential window was again set at 0.300 seconds.

The hammer input range was kept fixed at 1 Volt. The accelerometer input ranges were predominantly 310 mV, with the range being increased to 1 Volt when overloads were detected. Auto rejection of overloaded signals was enabled throughout.

The data capture for both the upper and lower surfaces was captured on one day. The lower surface data were captured from 1015 to 1253, giving 3.24 measurements per minute. The upper surface data were captured from 1315 to 1532, giving 4.18 measurements per minute. The increase in speed compared to last year is indicative of a smooth operation conducted by an outstanding team. Undoubtedly, previous experience with this specific structure also helped.

Data Quality

Overall, the data obtained for this trial are of a remarkably high quality. In-field quality monitoring was predominantly with the coherence function. Up to approximately 400 Hz, the coherence function was typically at 98% or better, with virtually no drop-outs. As is expected for impact-generated data, there was a drop-out in excitation power (and hence coherence and data quality). The first drop-out was near 550 Hz. Because of this drop-out, the data above about 450 Hz have a higher signal noise than the data below 450 Hz. However, the high-frequency data quality is still acceptable for many applications.

Figure 5 shows the coherence functions averaged for all measurements and all accelerometers, compared with the average coherence for the May 1999 and June 2000 trials. 100% coherence represents "perfect" data. Typically for large-scale vibration testing, anything over about 80% is deemed acceptable. As can be seen from the figure, overall the data quality is very high.

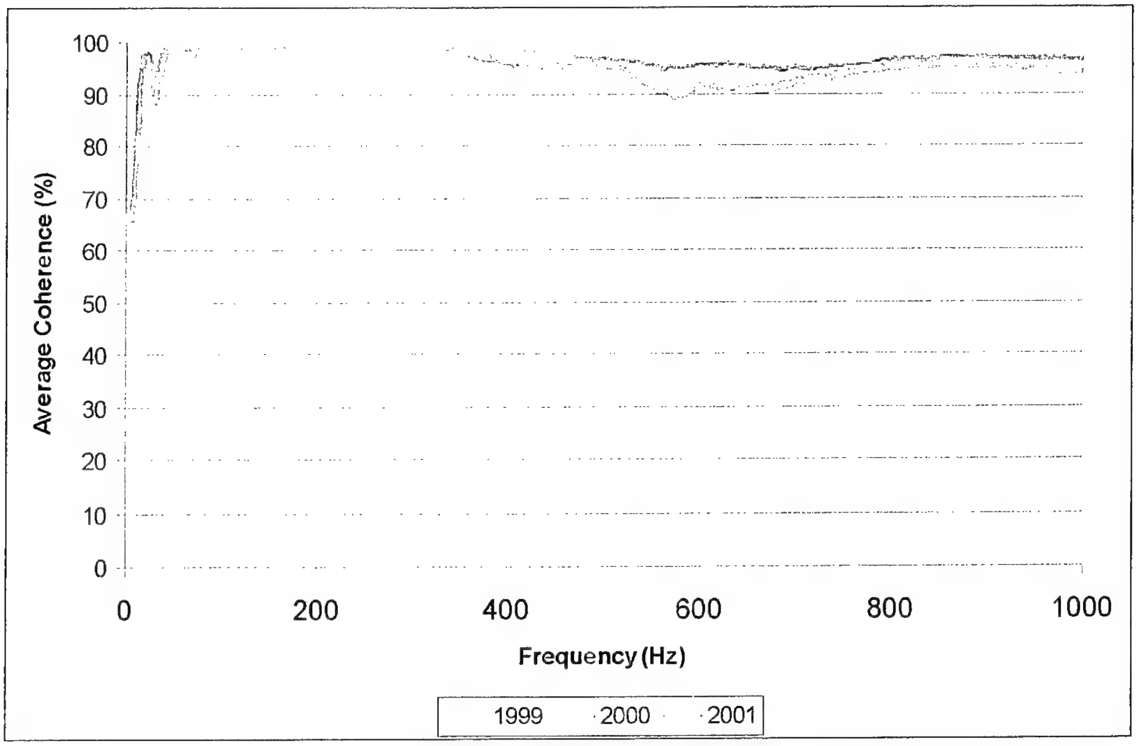

Figure 5. Average Coherence Function for the Three Years.

Data Translation

The raw analyzer data files were converted to a proprietary and archive-suitable format using the data conversion module included as part of a suite of programs provided by The Chartered Engineer, 2000 (Reference 5). This suite of programs is designed for large-scale experimental vibration testing and SIDER analysis. The archive-suitable files were then translated into a third file format. This final format is compatible with the commercial VES modal analysis suite supplied by Vibrant Technology, Inc., 1999 (Reference 6). Because of the way the modal analysis program operates on and changes the data files, this VES compatible file format is less suitable for archiving and other uses.

Modal Analysis

The modal analysis was conducted using the commercial program VES by Vibrant Technology, Inc. Accelerometer A was chosen as the reference accelerometer.

The natural frequencies and modal viscous damping ratios are presented numerically in Table 1. The data in this table are shown graphically in Figure 6 and Figure 7. The viscous damping ratios in both the table and figures have been corrected for the error introduced into the data by the analyzer window constant, Reference 6. The figures also include the results from the May 1999 and June 2000 trials.

Table 1. Natural Frequencies and Modal Viscous Damping Ratios Both Bridge Vibration Tests

Analysis Number	Natural Frequency (Hz)	Viscous Damping Ratio (%)
1	19.26	3.1
2	26.01	2.1
3	46.00	2.6
4	52.91	1.5
5	77.36	1.1
6	n/a	n/a
7	90.85	0.8
8	107.66	0.8
9	117.38	1.2
10	121.27	1.2
11	132.29	0.7
12	136.98	1.0
13	147.61	1.1
14	n/a	n/a
15	154.78	0.9
16	164.74	0.9

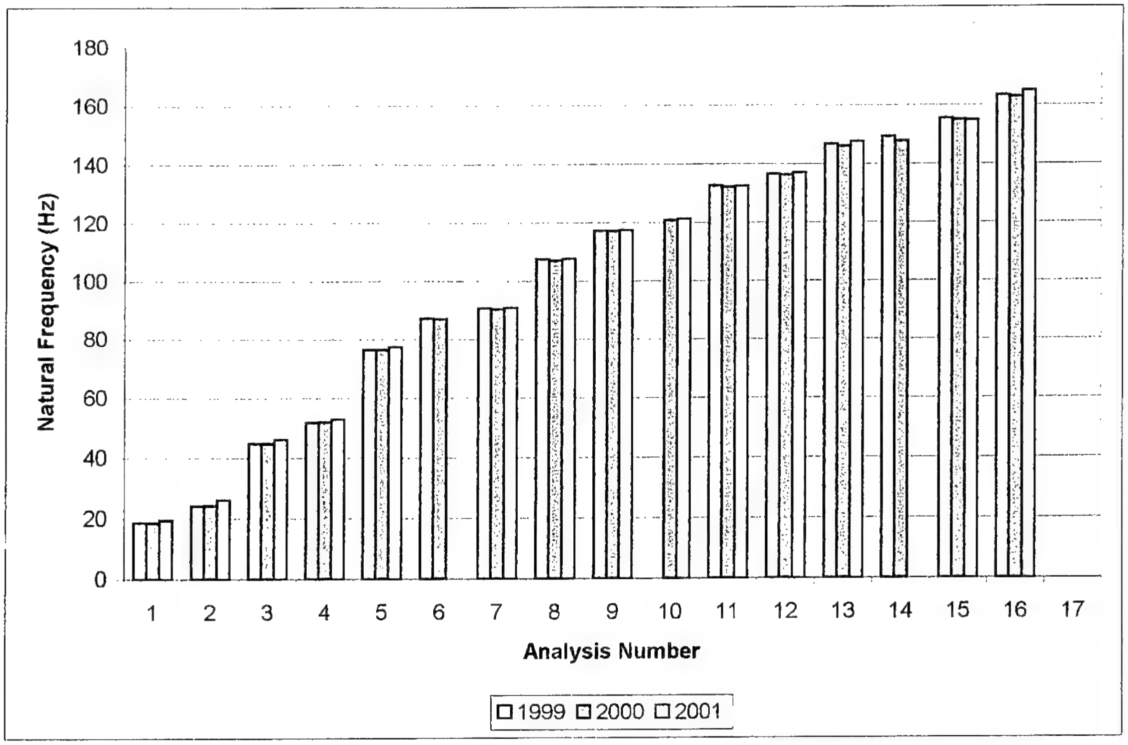

Figure 6. Natural Frequency vs. Analysis Number

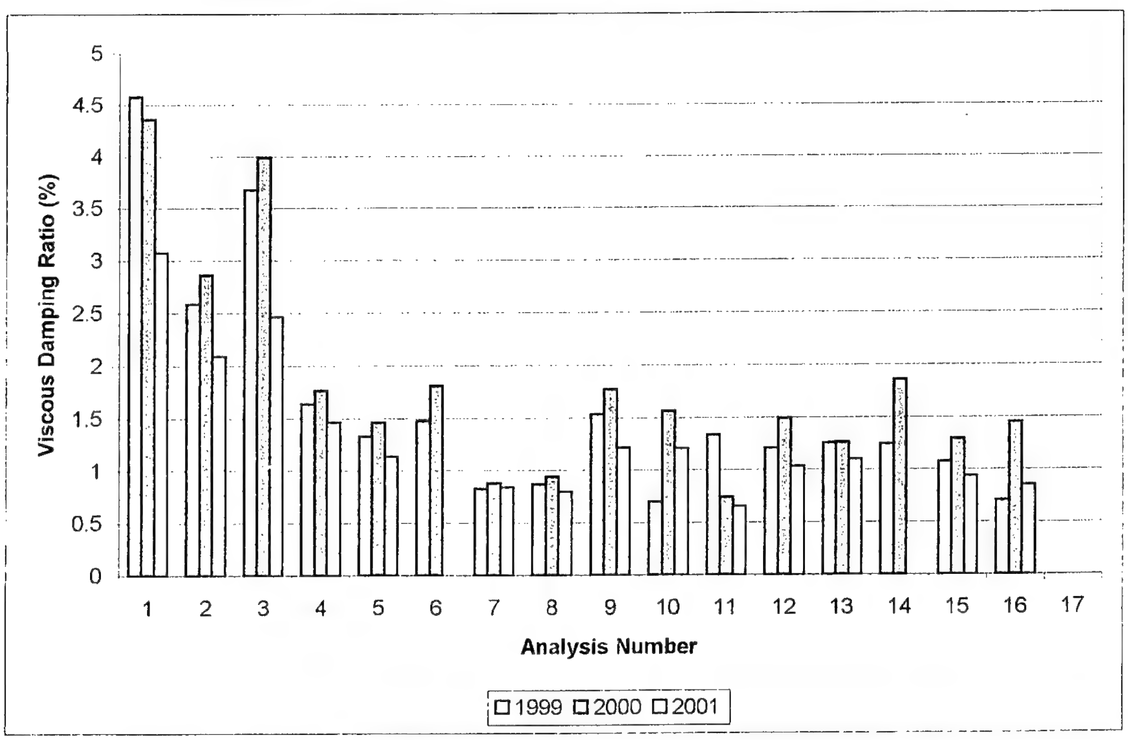

Figure 7. Modal Viscous Damping Ratio vs. Analysis Number

Of interest is the rate at which the natural frequencies are changing, since it would normally be expected that damage would cause a reduction in the natural frequencies. Figure 8 shows the rate of change of natural frequency for each analysis number. The rate is calculated as the linear regression of frequency versus time. The figure shows that all of the lower natural frequencies are increasing with time. This trend is contrary to expectations, and suggests that the level of structural degradation is very small, and having less effect on the natural frequencies than environmental effects. The increase in frequencies represents an increase in stiffness, since there is no observed loss in mass for this bridge.

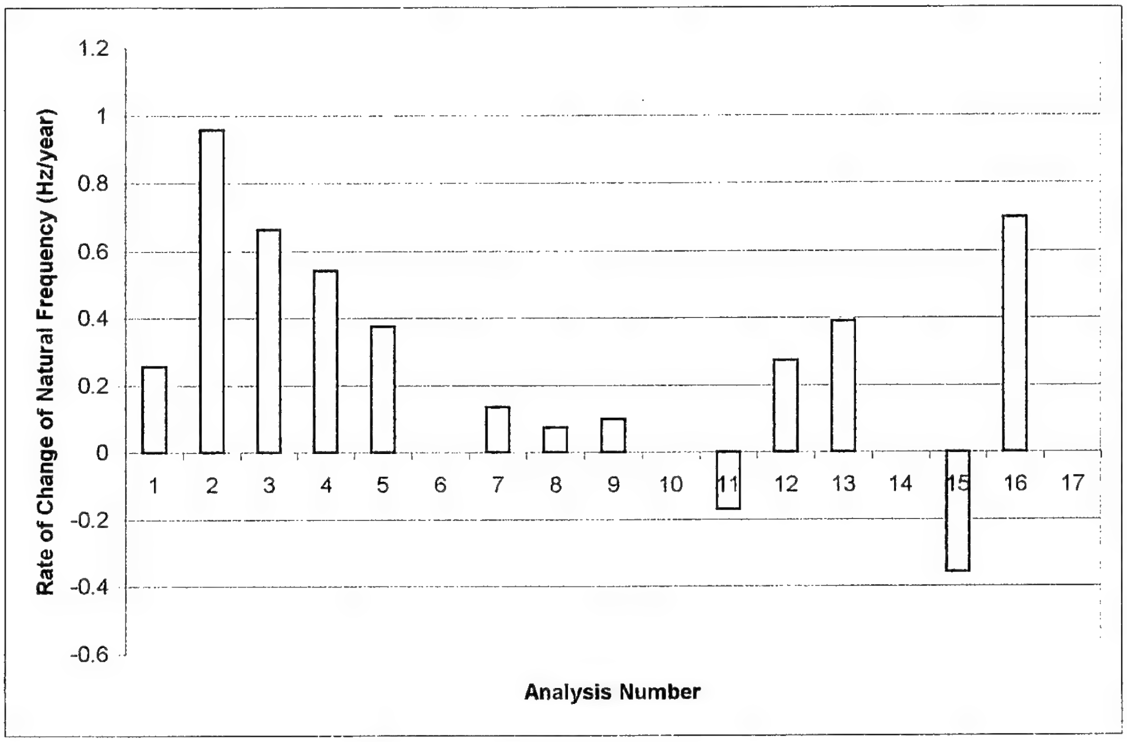

Figure 8. Rate of Change of Natural Frequency vs. Analysis Number

This report does not include any figures of the determined mode shapes. This is because they are almost identical to those determined in May 1999 and June 2000, and thus the figures in References 3 and 4 are relevant to the 2001 results.

Structural Irregularity and Damage Evaluation Routine (SIDER) Results

The SIDER procedure for locating structural irregularities and damage has been developed over the last few years, and is detailed in References 1 and 2. SIDER produces two different types of summary plot – raw and statistically enhanced. This report contains both types of plot. However, it is cautioned that the raw plot requires significant interpretation.

Figure 9 through Figure 11 show the raw SIDER results for 1999 to 2001 respectively.

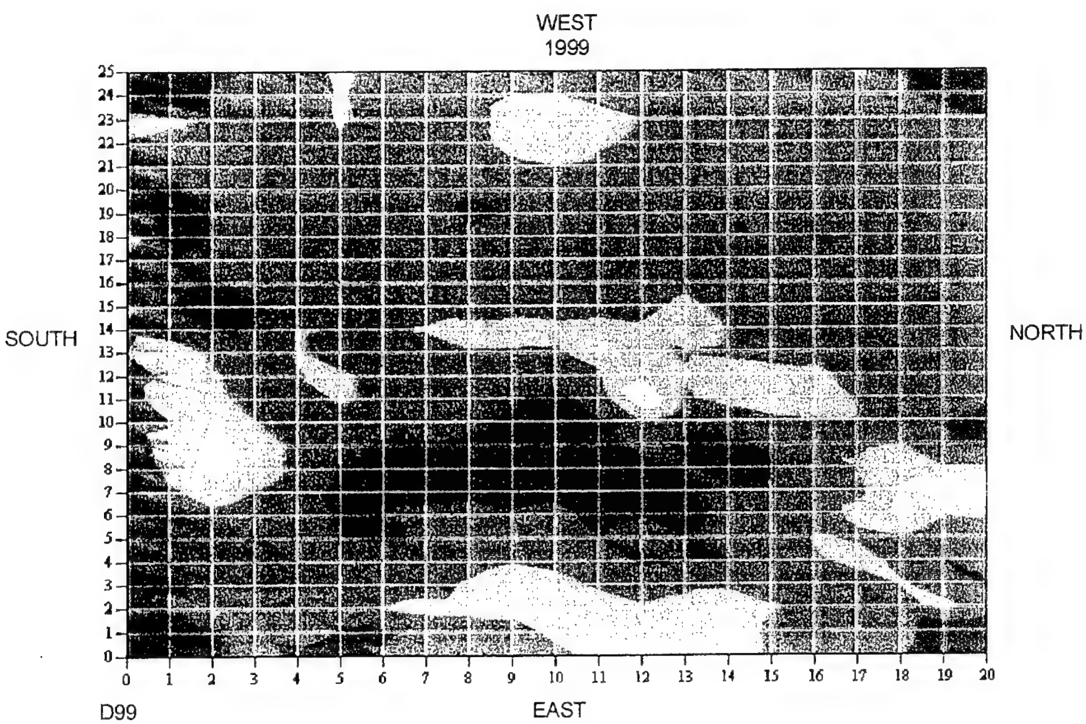

Figure 9. Raw SIDER for 1999

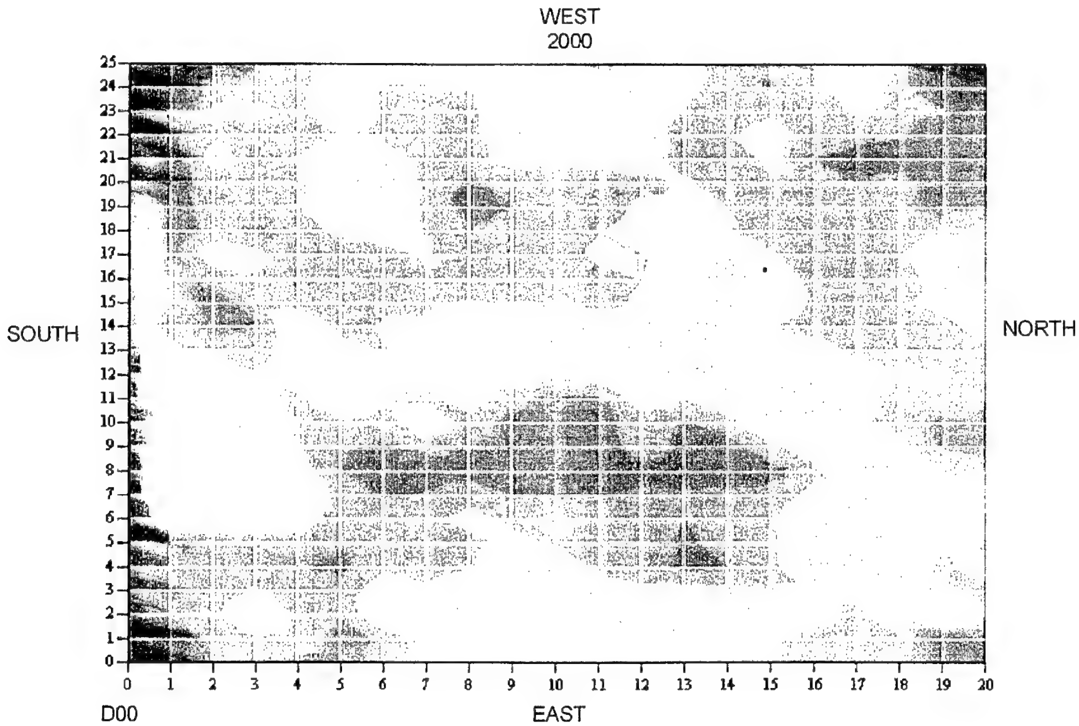

Figure 10. Raw SIDER for 2000

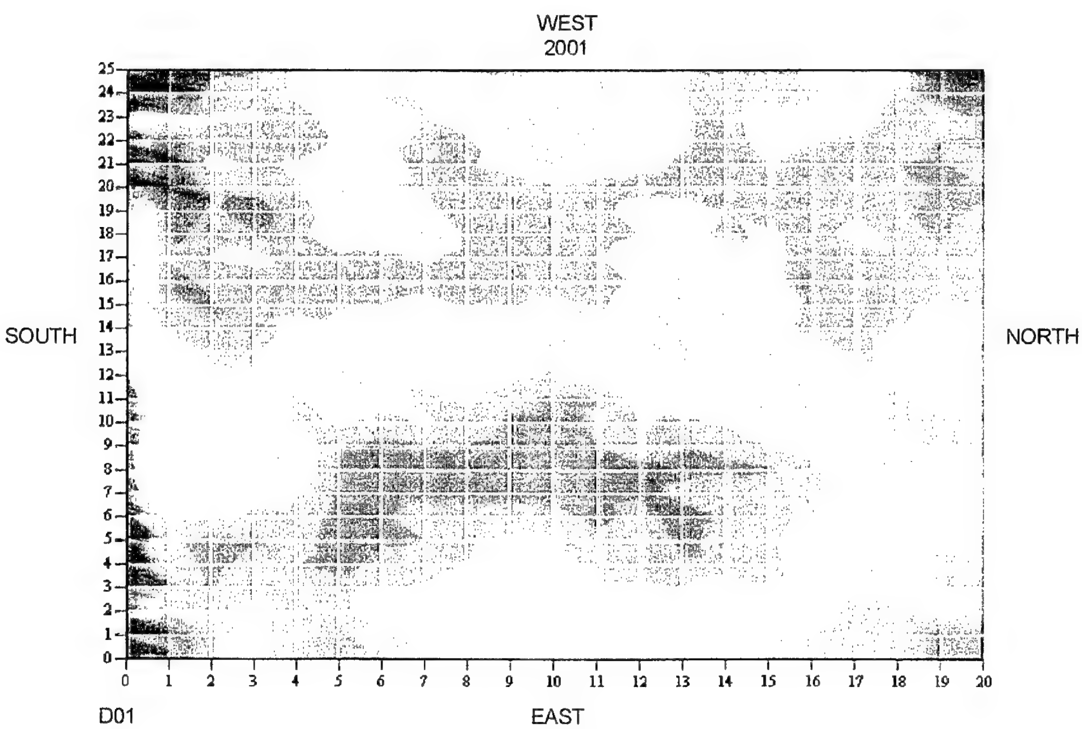

Figure 11. Raw SIDER for 2001

Figure 12 through Figure 14 show the statistically enhanced SIDER plots for 1999 to 2001 respectively.

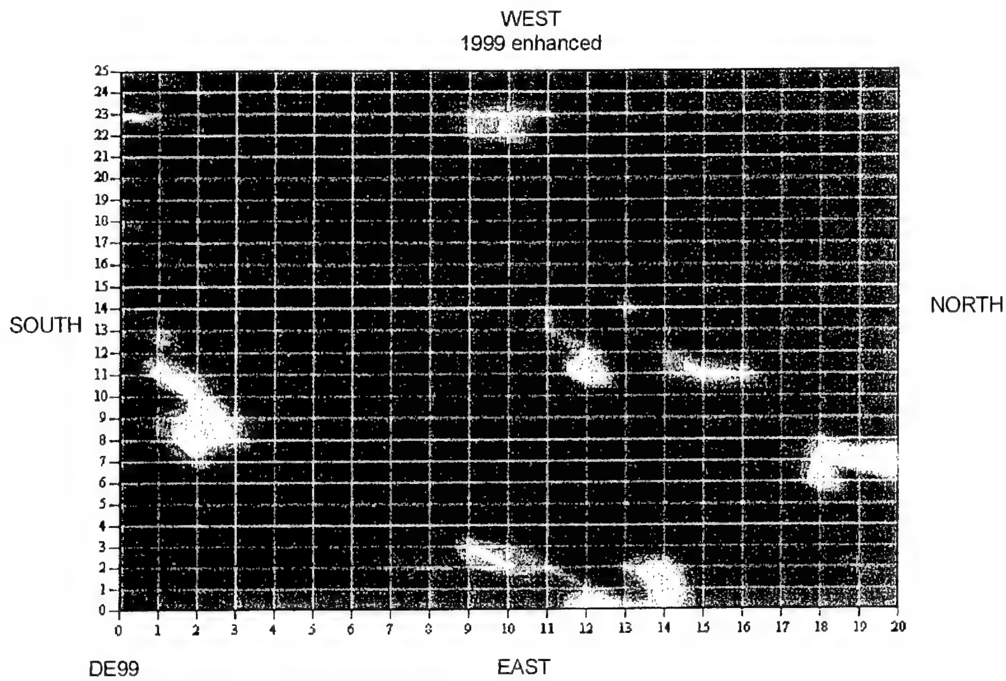

Figure 12. Statistically enhanced SIDER plot for 1999

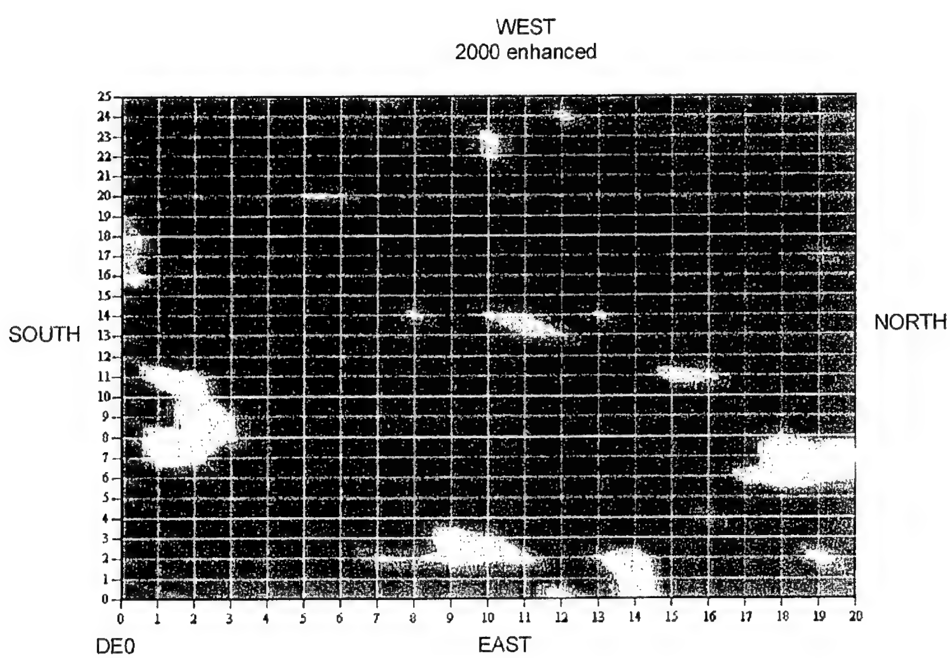

Figure 13. Statistically enhanced SIDER plot for 2000

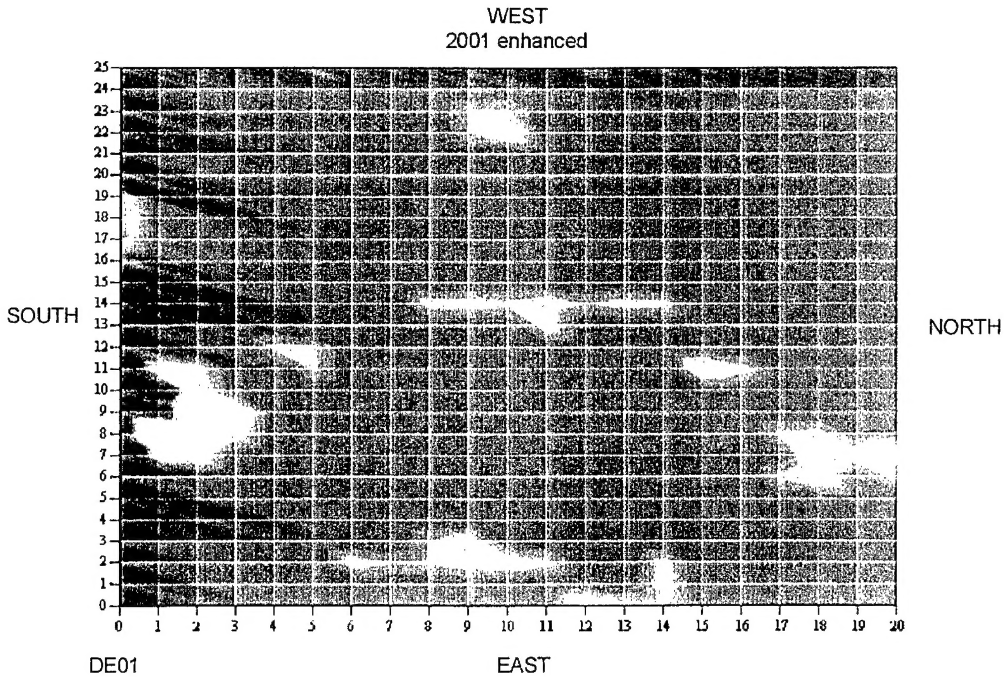

Figure 14. Statistically enhanced SIDER plot for 2001

Figure 15 and Figure 16 show the raw and statistically enhanced SIDER rate plots respectively.

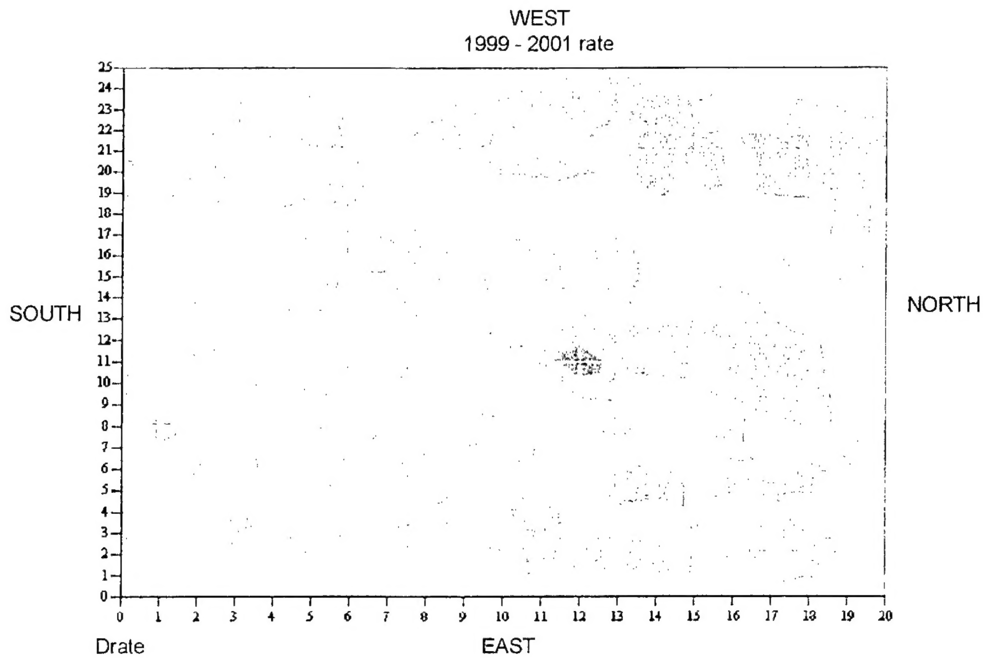

Figure 15. Raw SIDER rate summary plot

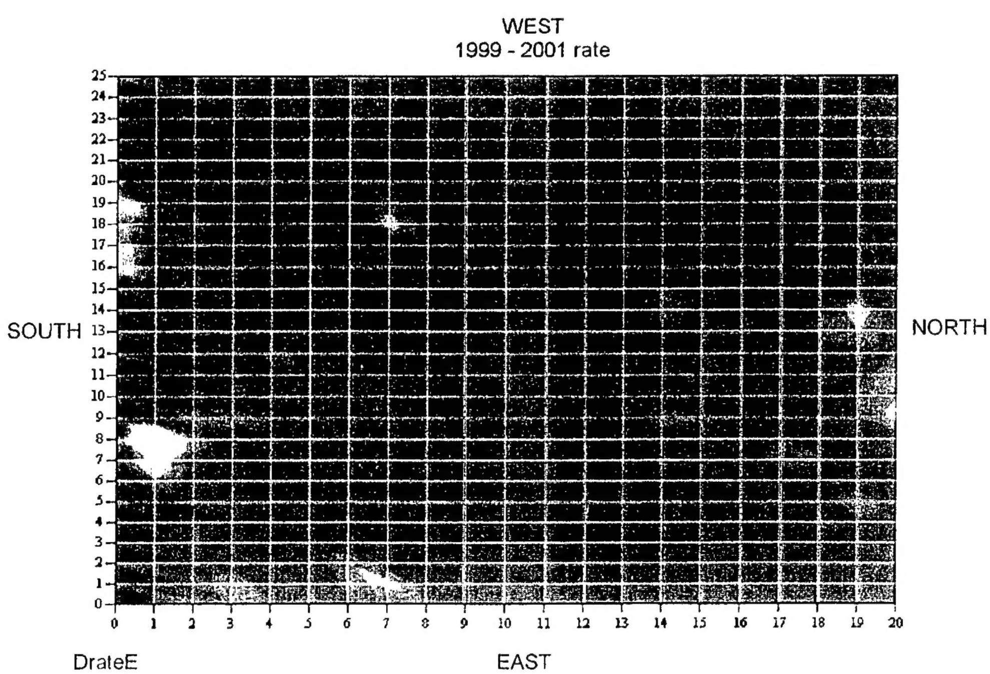

Figure 16. Statistically enhanced SIDER rate summary plot

Conclusions

The conventional results of the model testing of the bridge show that there was no significant overall change in the structure from its erection in 1999 until the testing that was conducted in 2001. These statements can be made by viewing the results of the change in resonant frequency and damping. One way in which degradation to the structure would manifest itself is in a reduction in stiffness. This would be detected through a reduction in the resonant frequency. The 2001 inspection determined the resonant frequency of the bridge to be the same as that determined in 1999 within the statistical error associated with this testing. In the case of the results of for 2001, the resonant frequency was actually shown to increase slightly. Statistically, this change is probably insignificant. From this result it is concluded that the bridge has not experienced a change in its structural performance after two years of service. An alternative method to assess changes in structural performance is to look at the change in damping of the structure over time. Degradation to a material or structure will manifest itself in an increase in damping. In the case of the bridge, there was actually a decrease in damping for the structure compared with the original results determined in 1999. Statistically, this change is probably insignificant. As such, one would say that there was virtually no change in the overall damping of the structure.

The results of the SIDER testing show that there were some changes in the bridge from 1999 to 2001. These results are easier to observe on the statistically enhanced SIDER summary plots. The SIDER analysis has indicated there is some change in the structure near the south-east portion of the bridge.

It should be pointed out that the SIDER technique is able to locate areas of changes in the structural integrity. With most other conventional vibration techniques, only global changes can be determined. As such, the SIDER analysis is a significant improvement over these conventional techniques.

Recommendations

The following recommendations are made:

a) That the non-destructive damage detection method continues to be developed to assess its applicability to locate damage in large-scale structures. The method has shown promise, but requires further development and validation.

b) That annual testing should be continued on the Delaware bridge. This bridge is an excellent structure for testing and developing methods suitable for naval applications. To the authors' knowledge, this is the first large-scale structure that has been made available for long-term research work of this kind. The support from other agencies makes its use a very cost-effective proposition.

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(further background material not referenced in this report)

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